ELECTRONIC FUNDAMENTALS

THEORY LESSON 22

ELECTRON TUBE CONSTANTS

22-1. Electron-Tube Constants

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22-3. Pentodes

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HOME STUDY SCHOOL

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Theory Lesson 22

INTRODUCTION

Before you read this lesson, we suggest that you review Theory Lessons 17 and 19, where the basic properties of diodes, triodes, and other electron tubes are discussed. Building upon the material presented in those two earlier lessons, this lesson prepares you to understand the operation of the various kinds of electron tubes that appear in the many radio, television, and other electronic circuits that are discussed in later lessons. In this lesson, you will learn about tube constants, more about characteristic curves, families of curves, tubes with remote and sharp cutoffs, and other worthwhile facts about tubes. Beginning with the next lesson you will apply this knowledge to typical amplifier circuits used in radio and television receivers.

22-1. ELECTRON-TUBE CONSTANTS

We learned in Lesson 19 that the flow of plate current in an electron tube of three or more elements (triode, tetrode, pentode, etc.) depends on several factors. Among these are the potentials that are applied to the plate, control grid, and screen grid (in tubes that have screen grids). Naturally there are other factors: the temperature of the cathode (which we will assume to be at normal operating level), and the maximum operating voltages and currents that the tube can withstand (which are part of the tube design and, once the tube is made, are things that we cannot change). So, it is not by chance that a certain amount of plate current flows in a particular type of tube when the grid voltage is so much and the plate voltage is at some fixed potential. Any normal tube of the same type would have the same flow of current provided that the operating conditions were the same. If you look up the 6J5 in your RCA Receiving Tube Manual you will find certain tube rating data (Fig. 22-1) called tube *constants* or sometimes, tube *parameters*. Tube-constants are expressed in numbers that permit us to

CLASS A_1 AMPLIFIER

Maximum Ratings:			
PLATE VOLTAGE		300 *max*	volts
GRID VOLTAGE, Positive Bias Value		0 *max*	volts
PLATE DISSIPATION		2.5 *max*	watts
PEAK HEATER-CATHODE VOLTAGE:			
Heater negative with respect to cathode		90 *max*	volts
Heater positive with respect to cathode		90 *max*	volts
CATHODE CURRENT		20 *max*	ma
Typical Operation:			
Plate Voltage	90	250	volts
Grid Voltage	0	−8	volts
→ Amplification Factor	20	20	
→ Plate Resistance	6700	7700	ohms
→ Transconductance	3000	2600	μmhos
Grid Bias (Approx.) for plate current of 10 μa	−7	−18	volts
Plate Current	10	9	ma
Maximum Circuit Value:			
Grid-Circuit Resistance		1.0 *max*	megohm

tube constants for 6J5 electron tube

Fig. 22-1

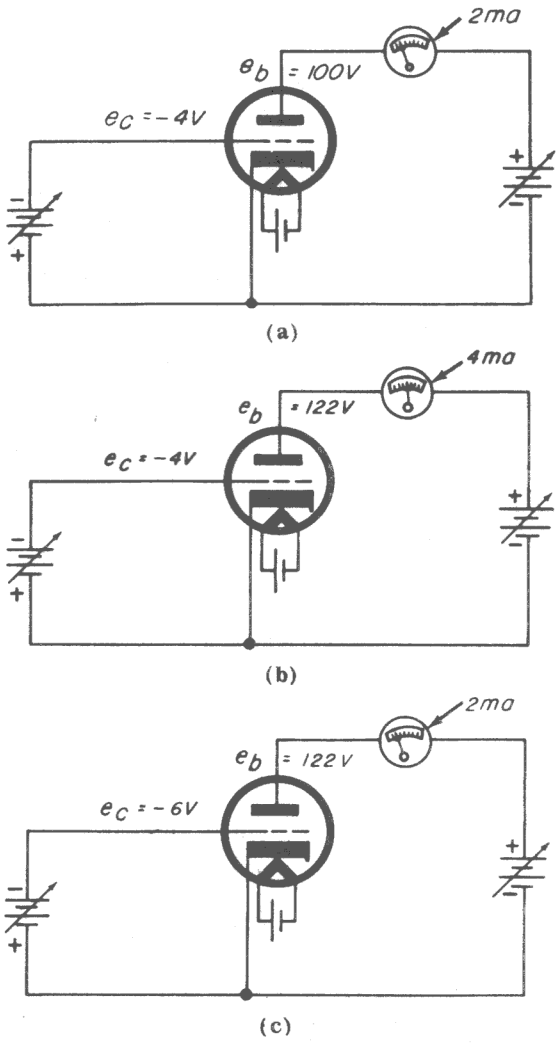


Fig. 22-2

compare the operation of one tube with another, so that we may select one or another for a certain purpose.

The most useful of these tube constants are *amplification factor*, *plate resistance*, and *transconductance*. Each will be explained in this lesson so that you may learn to understand and use it.

Amplification Factor. The amplification factor is the *ratio* between *a small change in plate voltage* that would produce a certain current change and *a small change in grid voltage* that prevents the current change and keeps the current constant. Let's break that definition down a little and see if we can't get a clearer idea of what it means. Look at Fig. 22-2*a*. It shows a triode (not the 6J5) with −4 volts on the grid and +100 volts on the plate. The meter shows that 2 ma of current flows. We know that we can increase the plate current flow by increasing the plate voltage and leaving the grid voltage as it is. So, we raise the plate voltage to 122 volts (making a plate-voltage change of 22 volts), which causes the plate current to rise to 4 ma (making a plate-current change of 2 ma), as shown in Fig. 22-2*b*. This takes care of the first part of our definition: we have *a small change in plate voltage that would produce a certain current change . . .*

Now we must make a change in grid voltage that will cancel the effect of the increased plate voltage and bring the plate current back to 2 ma. To reduce the current, we must make the grid more negative. We do this (Fig. 22-2*c*) and find that by making the grid −6 instead of −4, we bring the plate current back to 2 ma. So, a 2-volt change on the grid produces the same current change that was produced by a 22-volt plate-voltage change. This takes care of the second part of the definition: *and a small change in grid voltage that prevents the current change and keeps the current constant.*

The amplification factor is represented by the Greek letter μ (the same symbol that you use for *micro*) and is often written as *mu*. As a formula, the amplification factor is shown as follows:

$$\mu = \frac{\Delta e_b}{\Delta e_c}$$

where:

μ = amplification factor

Δe_b = small change in plate voltage

Δe_c = small change in grid voltage

For example, let's use the figures that we discussed above. Then:

$$\mu = \frac{\Delta e_b}{\Delta e_c}$$

$$= \frac{22}{2}$$

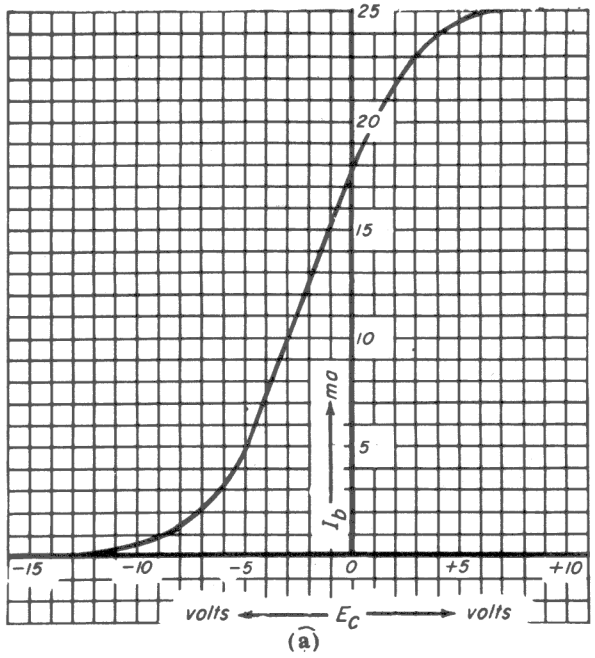
$$= 11$$

There is no unit of amplification, so the amplification factor is just a number. It

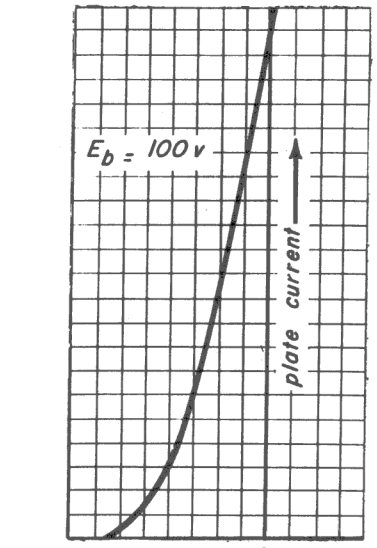
tells us, in this case, that the grid voltage of the tube is 11 times more effective in controlling plate current than is the plate voltage, because a change of 2 volts on the grid has the same effect on the plate current as a plate-voltage change that is 11 times as great. Within the normal operating range of the tube, the amplification factor or the mu (as we will call it from now on) of the tube is a constant – is always the same. For example, if the plate voltage were raised 33 volts, a 3-volt change on the grid, in a negative direction, would prevent a change in current. The ratio is still the same.

We can sum up by saying that mu is the ratio of a change in plate voltage to the change in grid voltage that results in the same current change. We are concerned about changes in grid voltage, plate voltage, and plate current because we often apply small a-c voltages to the grids of tubes in order to produce greater voltages of the same frequency and shape in the output of the tubes. As you know, we call this amplification. One practical use for mu is that it gives us an idea of how much a particular tube will amplify a signal voltage applied to the grid. For example, if a 2-volt signal is applied to the grid of the tube we have been discussing, it causes a change in plate current that, when the plate is loaded, causes a plate-voltage change of 22 volts. So we may say that the tube has amplified the signal 11 times. This may be better understood if we look at the current and voltage changes as they are shown on a graph.

Family of Curves. Look at Fig. 22-3*a*. It shows a triode characteristic curve that you saw in Lesson 19. This curve was drawn to illustrate a certain part of triode theory and does not represent the action of any particular tube. The curve shown in Fig. 22-3*b* is the characteristic curve of an actual tube. It shows the plate-current grid-voltage curve for a 6J5 when the plate voltage is 100. Notice that the curve does not show the portion where the tube saturates nor does it show operation in the area where the grid voltage becomes positive. This is because such a tube is normally operated in the linear portion of the curve, and where the grid remains negative. A single characteristic curve is seldom very useful. For that



(a)



characteristic curve for 6J5

(b)

Fig. 22-3

reason, we normally use a family of curves (Fig. 22-4), which, as you learned in Lesson 17, is a group of curves all drawn on the same graph.

The family of curves shown in Fig. 22-4 is called the *grid* family. Each curve is identified by the value of plate voltage under which the plate-current and grid-voltage measurements represented by the curve were taken. The curves look somewhat alike: each has a linear portion and a portion that curves to meet the x-axis and indicates the value of grid voltage that produces

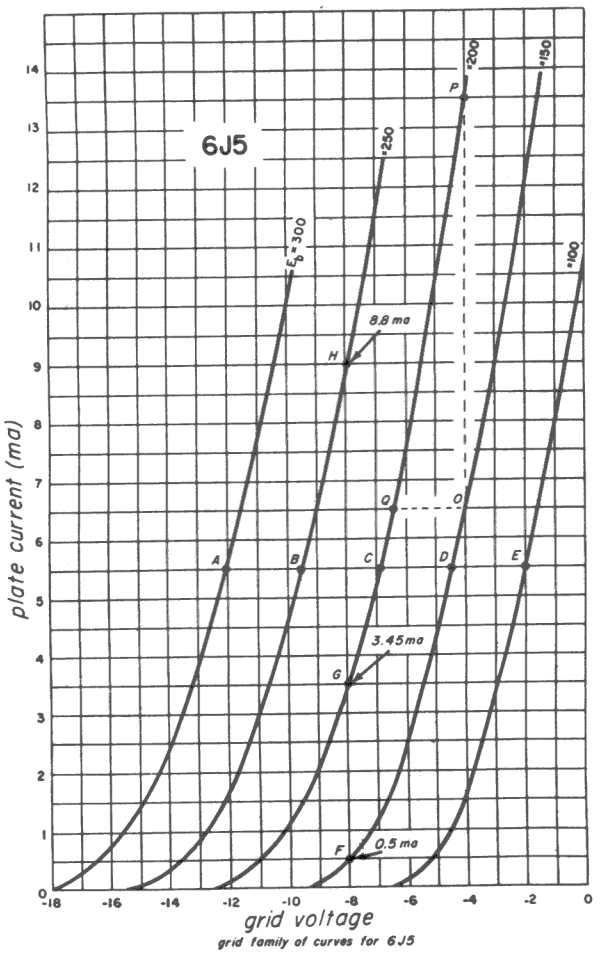


Fig. 22-4

plate-current cutoff. For example, −9.3 volts causes cutoff when there is 150 volts on the plate, while −15.5 volts are needed to cut off the plate current when 250 volts is on the plate. You will note that as the plate voltage becomes greater, a greater negative grid voltage is required to produce cutoff.

The grid family of curves is useful because it tells us several things. For example, look again at the grid family for the 6J5 tube. Find Point *A* on the 300-volt curve. It shows that 5.5 milliamperes of plate current flows when the voltage on the grid is −12.1 volts. The same amount of plate current flows at Point *B* on the 250-plate volt curve, but now the grid voltage is −9.5 volts. We see, too, that the same plate current flows at Point *C* on the 200-volt curve, Point *D* on the 150-volt curve, and Point *E* on the 100-volt curve. However, in each case the grid voltage differs. It is −6.8 volts at *C*, −4.5 volts at *D*, and −2 volts at *E*. From this, we can see that by changing the value of the grid voltage, we can keep the plate current at the same value, even though the plate voltage is varied.

Look at the grid family again, and find points *F*, *G*, and *H* on the vertical line that represents a grid voltage of −8. You can see that 0.5 milliampere flows with 150 volts on the plate, that 3.45 milliamperes flows with 200 volts on the plate, and 8.8 milliamperes flows with 250 volts on the plate. From this, we can see that the plate current rises with each increase in plate voltage as the grid voltage is kept constant.

Of course, each curve of the grid family shows the changes in plate current as the grid voltage is varied and the plate voltage remains constant. This you learned in Lesson 19.

We can use the grid family of curves to find the mu of the tube. Suppose we want to use the grid family to find the mu of 6J5. For example, select point *O* in the linear portion of the 150 plate volts curve, which shows that 6.5 milliamperes of plate current flows with −4 volts on the grid. Now, let us assume that we are going to raise the potential of the plate to 200 volts without changing the grid voltage. If we follow the −4 volt grid line upward until it meets the 200-volt plate voltage curve at point *P*, we find that with 200 volts on the plate, and −4 volts on the grid, the plate current should be 13.5 milliamperes. But, in finding the amplification factor, we want to keep the plate current constant, so if we follow the 6.5 milliampere line until it meets the 200 plate voltage curve at point *Q*, we find that the grid voltage necessary to keep the plate current constant at 6.5 milliamperes is −6.45 volts. Therefore, a change of 2.45 volts on the grid has the same effect on the plate current as a change of 50 volts on the plate. Therefore, we can find mu by using the formula:

$$\mu = \frac{\Delta e_b}{\Delta e_c}$$

$$= \frac{50}{2.45}$$

$$= 20.4$$

Look again at Fig. 22-1 and you will see that the manufacturer rates the 6J5 as having a mu of 20. The value that we found for mu is just 2% higher than the manufacturer's rating, which is about as close as we can expect to come. Greater accuracy may sometimes be obtained by using a smaller change in plate voltage over a smaller change in grid voltage.

Let's look again at our grid family of curves and see what else it can tell us. Let's assume that we are operating with 200 volts on the plate at point *Q*, (–6.45 volts on the grid). The plate current is 6.5 milliamperes. If we were to change the grid voltage to –4 while we maintained the same plate voltage, the plate current would rise 7 milliamperes to point *P* for a value of 13.5 milliamperes. To prevent the plate current from rising to this point, it would be necessary to reduce the plate voltage to 150 volts (point O on the 150-volt curve). From this, we can see that a 2.45-volt change in grid volts produces a 7 milliampere change in plate current, which is equal to a 50-volt change in plate volts.

Plate Family of Curves. Figure 22-5 shows another set of curves for the 6J5 tube. It is called the plate family of curves, because it shows changes in plate current. Each curve represents a change in plate current for a change in plate voltage, with the grid voltage remaining constant. As you will note, each curve is marked for a particular value of grid voltage. The plate family of curves is used more often than the grid family. You will notice that no curves are shown for positive values of grid voltage because, as we said before, the 6J5 and similar tubes are seldom operated in circuits where grid voltage is allowed to go positive. The lower portion of each curve starts along the plate-voltage axis, at the point where the plate voltage and the value of grid voltage that the curve represents produce plate-current cutoff.

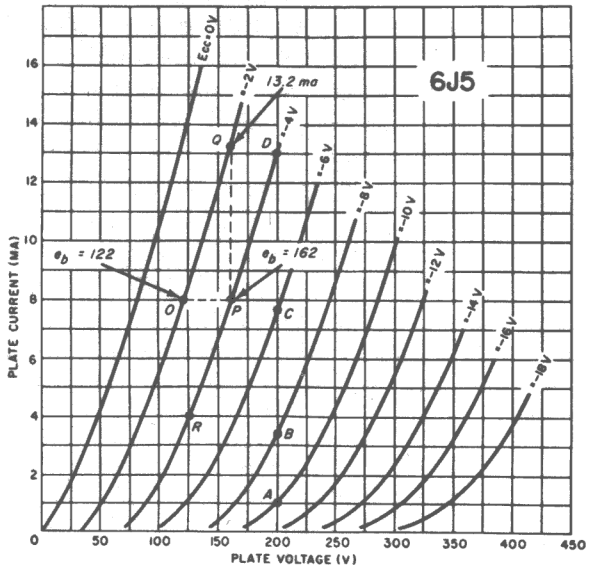


plate family of curves for 6J5

Fig. 22-5

We can learn much the same things from the plate family of curves as we did from the grid family, though at times this information is more readily obtained from the plate family. For this reason, the plate family is more often used. Let's look at the plate family of curves for a moment and see what it can tell us. We can see, for example, that with –4 volts on the grid, and 150 volts on the plate, the plate current is 6.5 milliamperes. You recall this is the same value that we found at the grid family of curves for the same voltage conditions.

Just as we did with the grid family of curves, we can follow any curve in the plate family and see that the plate current rises as plate voltage increases and the grid voltage remains constant. If we look along the 200-volt-plate voltage line to points *A*, *B*, *C*, and *D*, we find that if the plate voltage remains constant and the grid voltage becomes less negative, the plate current rises.

The plate family may be used to find the amplification factor. From point *O* on the –2 volt curve, where the plate voltage is 122 and where the plate current is 8 milliamperes, let's follow the 8-milliampere line to point *P* where it meets the –4 volt grid curve and where the plate voltage is 162. From this point, we can draw a line parallel with the 150-volt plate voltage line until it meets –2 volt grid curve at point *Q*. This shows us that a change of 2 volts on the grid or 40 (162-122) volts on the plate produces a current change of 5.2 (13.2 – 8.2)

ma. Mu may be found by using the formula:

$$\mu = \frac{\Delta e_b}{\Delta e_c}$$

$$= \frac{40}{2}$$

$$= 20$$

This value of mu agrees with that shown in the tube manual. So, you can see we can use either the grid family or the plate family to find mu.

Practical electron-tube triodes are divided roughly into three groups: *low-mu* triodes with amplification factors of less than 8, such as the 6B4-G with a mu of 4.2; *medium-mu* triodes with amplification factors of 8 or more and less than 50, such as the 6J5 with a mu of 20; and *high-mu* triodes with amplification factors of 50 or more, such as the 6G5 with a mu of 100 or the triode section of your 6AT6 with a mu of 70.

While the mu for almost any triode is practically constant when operated under rated voltages, there are some triodes, such as the 6C4 and others, that have amplification factors that vary as different operating voltages are applied. The application of such tubes is discussed in later lessons.

Plate Resistance. The second of the electron-tube constants in which we are most interested is the plate resistance. When we studied diode theory, we learned that the plate resistance of a tube may refer to either its d-c plate resistance or its a-c plate resistance. The d-c plate resistance, abbreviated R_b, refers to the opposition that the tube offers to plate current when the voltages are constant. It is found by using Ohm's law. For example, point R on the 4-volt curve shows that 4 ma of plate current flows when there is 125 volts on the plate. Therefore:

$$R_b = \frac{E_b}{I_b}$$

$$= \frac{125}{0.004}$$

$$= 31{,}000 \quad \text{(approx)}$$

However, the d-c plate resistance of the tube is of little value to us, because normally the plate current and the grid and plate voltages are constantly changing under operating conditions. So, when we speak of plate resistance, we normally refer to the a-c plate resistance, which is abbreviated r_p, although in some places it may be written as R_p.

The plate resistance of the tube is the ratio of a small change in plate voltage to a small change in plate current, with the grid voltage constant. In formula form, it is written:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

We may use the grid family of curves to find a-c plate resistance. The 6J5 grid family is shown again in Fig. 22-6. Let us choose point O on the 150-volt curve and, because the grid voltage must remain con-

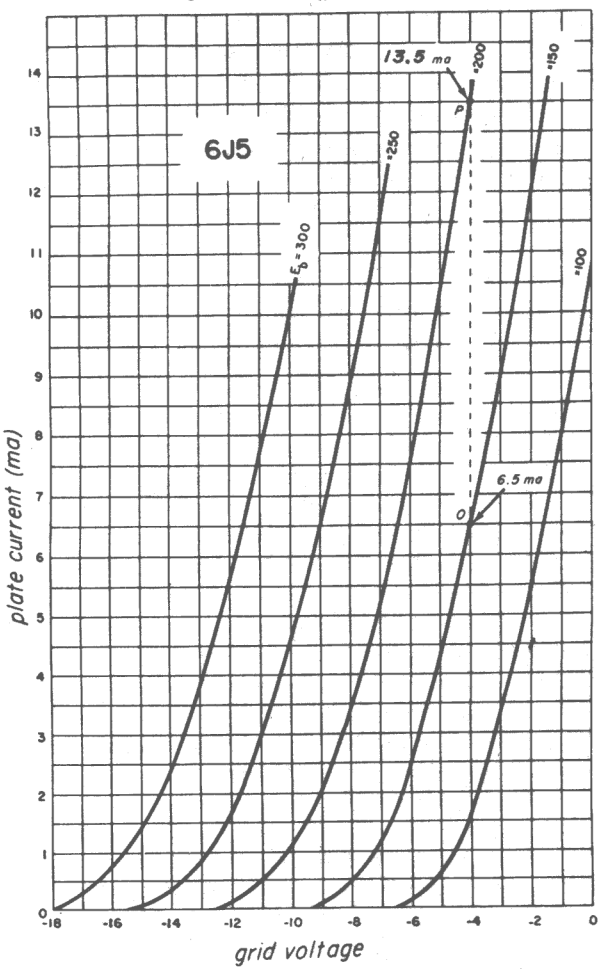


Fig. 22-6

stant, let us follow the –4 volt grid line until it meets the 200-volt curve. Let us call this point *P*. The plate current at *O* is 6.5 ma. At *P* it is 13.5 ma. So a change of 50 volts on the plate causes a change of 7.0 ma in plate current. The a-c resistance may be found by using the formula:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

$$= \frac{50}{0.007}$$

$$= 7{,}143 \text{ ohms}$$

This value is consistent with those given for the typical operation of the 6J5 in your RCA tube manual. Therefore the plate resistance for a plate voltage of 90, and a grid voltage of zero, is given as 6,700. Where there is 250 volts on the plate and –8 volts on the grid, the plate resistance is given as 7,700 ohms. The value we found lies between the two values given by the manufacturer. From this, you can see that the a-c plate resistance is not a relatively fixed value, as it is for the amplification factor. The plate resistance changes with a change in operating conditions, as we shall see shortly.

Look at Fig. 22-7, where the plate family for the 6J5 tube is shown again. Let us select a point *A* in the linear portion of the –6-volt grid voltage curve, at which the

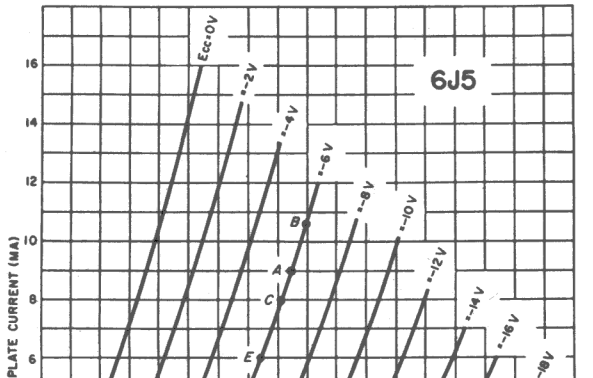


Fig. 22-7

plate voltage is 212 and the plate current is 9 ma. Working upward on the –6-volt grid curve, we mark off a point *B*, which is 10 volts higher in plate voltage than point *A*. Then, working down on the same curve, we locate point *C*, which is 10 volts lower than point *A* in plate voltage. The plate current at point *B* is 10.4 ma and at point *C* is 7.9 ma. Therefore, a change of 20 volts on the plate produces a plate-current swing of 2.5 ma. The a-c plate resistance at this operating point is approximately 8,000 ohms.

Let's select another point on the same curve and mark it *D*. At *D*, the plate voltage is 176. Above *D* on the same curve, we will mark off a point *E*, where the plate voltage is 187 volts; below *D*, we mark off point *F*, which represents 167 plate volts. The plate current at point *E* is 6.1 ma and at point *F* is 4.1 ma. Therefore, a change of 20 volts on the plate produces a change of 2.0 ma in plate current. The plate resistance at this operating point turns out to be 10,000 ohms.

From our a-c plate resistance calculations, we may conclude that the plate resistance becomes smaller as grid voltage becomes less negative. We may also conclude that the plate resistance decreases as the plate voltage increases (with the grid voltage remaining constant).

Transconductance: The third of the tube constants we are most interested in is called *transconductance* or mutual conductance. Transconductance is the ratio of a change in plate current to a change in grid voltage when the plate voltage remains constant. The unit of transconductance is the *mho*, which is ohm spelled backwards. It is abbreviated G_m. The G_m formula looks like this:

$$G_m = \frac{\Delta i_b}{\Delta e_c}$$

For example, if an electron tube with 250 volts on the plate has a change of 2 ma in plate current for a grid voltage change of 1

volt, the transconductance may be found:

$$G_m = \frac{\Delta i_b}{\Delta e_c}$$

$$= \frac{0.002}{1}$$

$$= 0.002 \text{ mho}$$

Because most practical values of transconductance equal a decimal fraction of a mho, a more practical unit of transconductance is the micromho (1/1-millionth of a mho). Therefore, the value of transconductance that we just found is normally given as 2,000 micromhos.

We may find the transconductance of a tube by means of either the grid or plate family of curves. For example, if we use the grid family (Fig. 22-8), we might select a curve that represents a plate voltage of 200. Point *O* on the 200-volt curve shows a plate-current flow of 5.2 ma with a grid voltage of −7 volts. Let us travel along the same curve to point *P* where the curve intersects the −6-volt grid line. The plate current at this point is 7.6 ma. So a grid-voltage change of 1 volt produces a plate current change of 2.4 ma. The transconductance may be found by using the formula:

$$G_m = \frac{\Delta i_b}{\Delta e_c}$$

$$= \frac{0.0024}{1}$$

$$= 2{,}400 \ \mu\text{mhos}$$

Let's try another: Let's find the point where the 250-volt curve intersects the −8-volt grid line. Call this point *R*. Now travel along the 250-volt curve until it meets the −7-volt grid line. Call this point *S*. The plate current flow at *R* is 8.8 ma and at *S* is 11.7 ma. The current change is 2.9 ma. We may find the transconductance by using the formula:

$$G_m = \frac{\Delta i_b}{\Delta e_c}$$

$$= \frac{0.0029}{1}$$

$$= 2{,}900 \ \mu\text{mhos}$$

Looking at the plate family of curves in Fig. 22-9, find point *O* on the −2 volt grid

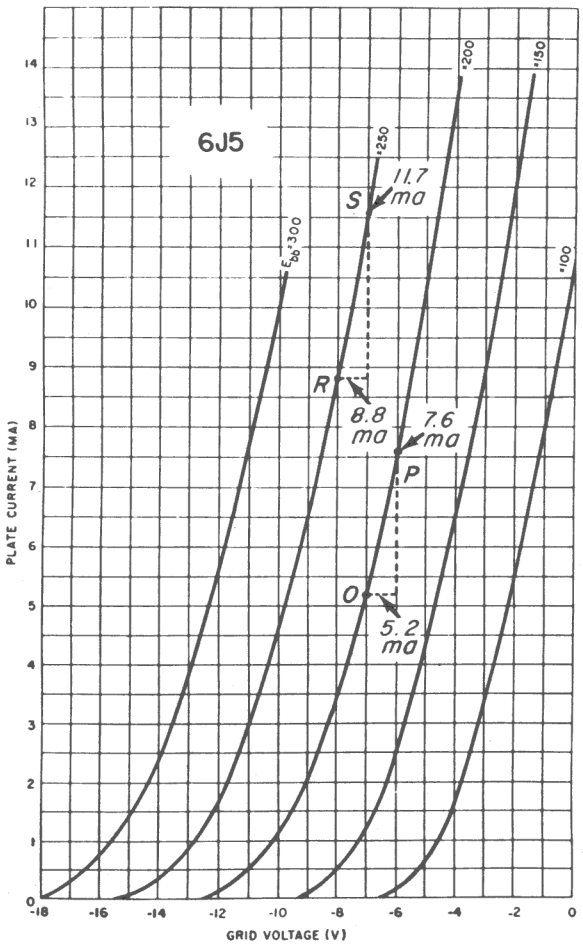


Fig. 22-8

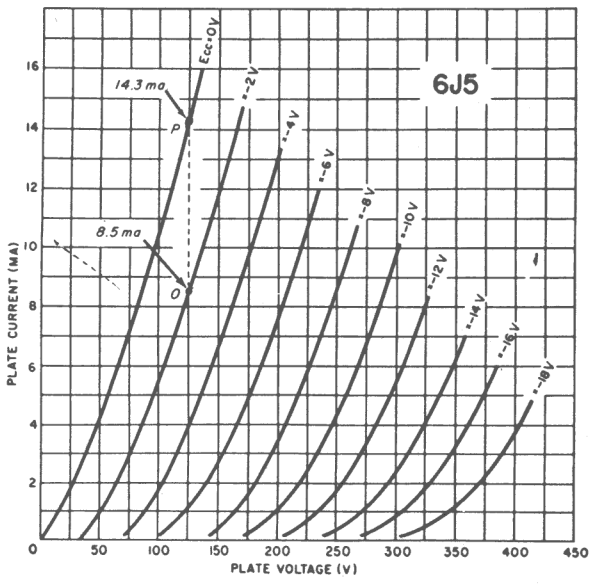


Fig. 22-9

voltage curve. This shows that with 125 volts on the plate, the plate current is 8.5 ma. Because the plate voltage must remain constant, we follow the 125-volt plate-voltage line until it meets the zero-grid-voltage curve at point *P*. The plate current at this point is 14.3 milliamperes. Thus, a grid voltage change of 2 volts produces a plate current change of 5.8 ma. We may find the transconductance thus:

$$G_m = \frac{\Delta i_b}{\Delta e_c}$$

$$= \frac{0.0058}{2}$$

$$= 2{,}900 \ \mu\text{mhos}$$

If you refer to the 6J5 tube constants in your RCA Tube Manual, you will find that transconductance is rated at 3,000 when there is 100 volts on the plate and zero volts on the grid. In actual practice, to produce the grid-voltage swing between zero and −2 volts, our operating point would be halfway between zero and −2 volts, or −1 volt. Therefore, the operating conditions for which we found a transconductance of 2,900 micromhos are slightly different than the conditions shown in the tube manual. For that reason we should expect to find a value of transconductance somewhat different than that shown in the tube manual.

Like the a-c plate resistance, the transconductance of a tube varies somewhat with the operating conditions. However, the product of the plate resistance and the transconductance is always equal to the amplification factor. So in formula form we can say:

$$\mu = G_m \times r_p$$

(The proof of this is given in the appendix for this lesson.) Going one step further, we find that:

$$r_p = \frac{\mu}{G_m}$$

and

$$G_m = \frac{\mu}{r_p}$$

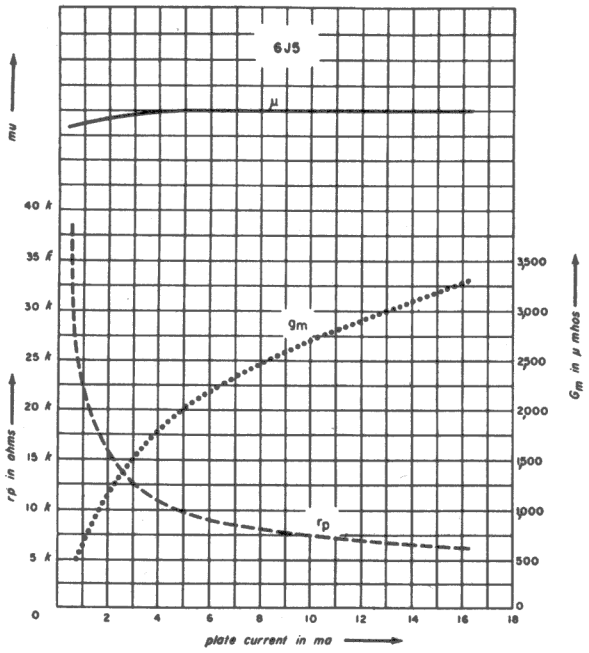


Fig. 22-10

For example, your RCA Tube Manual shows that with 90 volts applied to the plate of a 6J5 tube and zero volts to the grid, the plate resistance is 6,700 ohms and the transconductance is 3,000 μmhos. From these figures, we can calculate the mu of the tube in this way:

$$\mu = G_m \times r_p$$

$$= 0.003 \times 6{,}700$$

$$= 20.1$$

This value is close enough to the mu of 20 as listed in the tube ratings. Note that it is necessary to convert micromhos back to mhos in order to get a correct answer. The graph in Fig. 22-10 shows how these 6J5 tube constants vary in relation to each other.

TRIODE

Summary. From our calculations and from our study of Fig. 22-10, we can see that, for the most part, the mu of the tube remains the same over the normal range of operating voltages. The plate resistance (r_p) and transconductance vary with operating voltages. The plate resistance is high for low values of plate current, which are caused by either low plate voltage or high negative grid voltage or both. The plate resistance decreases as the plate current increases, which it does when the plate voltage becomes higher or the grid voltage becomes

less negative or both. The transconductance varies greatly, too, but oppositely to the plate resistance: as the plate resistance decreases, the transconductance increases.

While we have discussed these tube constants with respect to triodes, and to the 6J5 triode in particular, mu, r_p, and G_m are used also in discussing and comparing tetrodes, pentodes, or any electron tube of three or more elements.

22-2. TETRODES

From your study of Lesson 19, you recall that a tetrode is a four-element tube that has two grids: one called the control grid (G_1) and the other called the screen grid (G_2). You may recall, too, that one disadvantage of the tetrode is in its secondary emission. The action of a typical tetrode is shown in Fig. 22-11. These curves are for an early type 24-A tube, a tube that is now made only for replacement purposes. However, the 24-A characteristics are such that these operating curves show certain things that you want to know about tetrode action. There are three curves. One, marked i_b, shows the variations in plate current that result from changes in plate voltage (E_b); another, marked i_{c2}, shows the variations in screen-grid current that result from variations in E_b and a fixed screen-grid voltage (E_{c2}) of 90 volts; and the third curve, marked $i_b + i_{c2}$, shows the sum of the screen and plate currents. Let's look at Fig. 22-11 and see what it can tell us.

Looking along the Y axis, we find that, when the plate voltage is zero and there is 90 volts on the screen, the screen current (i_{c2}) is 5.2 ma and the plate current (i_b) is 0.5 ma. Of course, the screen attracts electrons from the heated cathode because it is 90 volts positive with respect to the cathode. The 0.5 ma of plate current is the result of some fast-travelling electrons passing through the turns of the screen grid and landing on the plate. The sum of the screen and plate currents (5.2 + 0.5 or 5.7 ma) is shown by the top curve marked $i_b + i_c$. As the first few volts of B+ are applied to the plate, the screen current starts dropping and the plate current rises. When the plate voltage rises to a point beyond 5 volts, the electrons speed up and strike the plate with such force that they cause electrons to be freed from the plate and form a secondary emission. When the plate voltage reaches

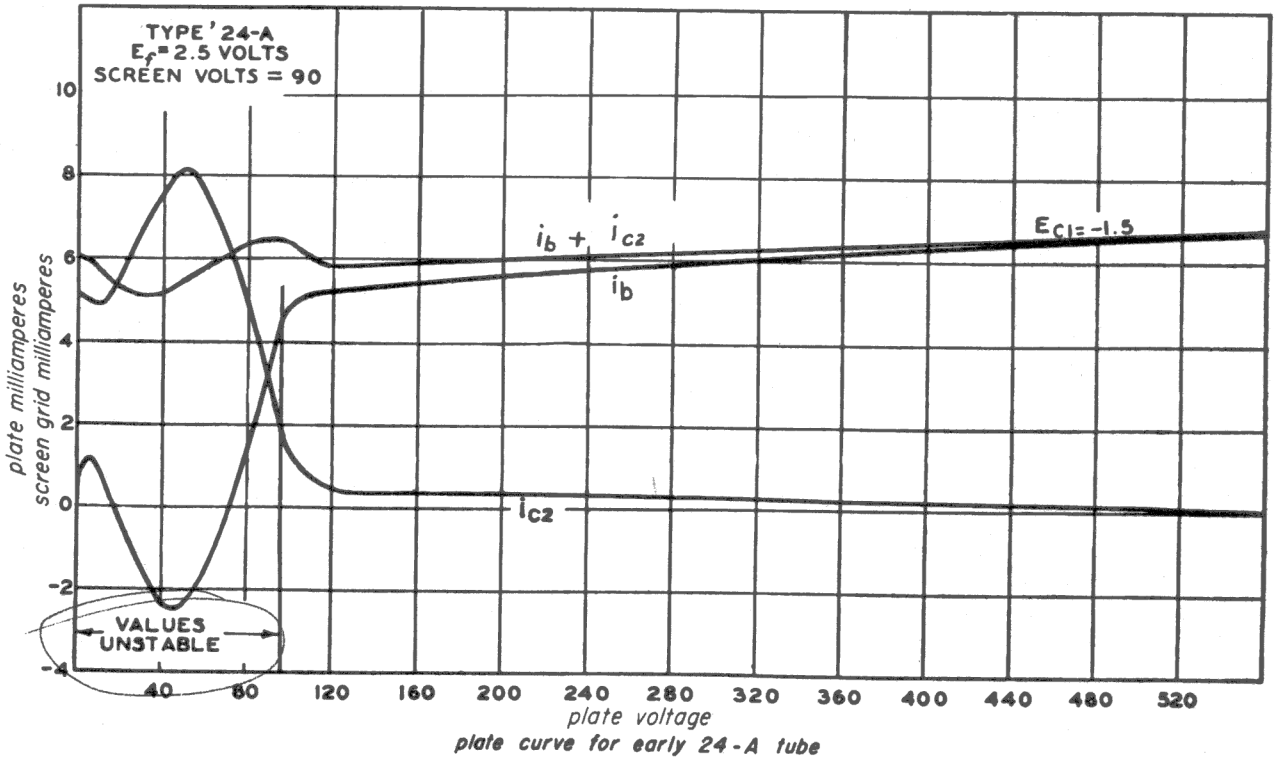


plate curve for early 24-A tube

Fig. 22-11

about 20 volts, the number of primary electrons emitted by the cathode that reach the plate equals the number of secondary electrons emitted by the plate, so that there is effectively no plate current. When this happens, the sum of i_b and i_c equals the screen current. As the plate voltage rises to a point between 40 and 50 volts, the secondary emission becomes larger and the number of primary electrons that reach the plate are outnumbered by the secondary electrons, so that the resultant current is negative – away from the plate and toward the screen. In this area, the sum of the screen and plate currents is shown as being less than the screen current. This is because the current shown as being negative in direction is subtracted from the positive screen current to get the sum of the currents.

As the plate voltage continues to increase, the plate current rises rapidly and the screen current decreases at the same rate until the plate voltage approaches 90 volts and the plate and screen currents level off. From this point on, changes in plate voltage have little or no effect on the plate current.

From these curves, we can see that the total current ($i_b + i_c$) is affected only slightly by changes in plate voltage. We can also see that when the plate voltage exceeds the screen voltage and does not fall below it, the plate voltage has practically no effect on the plate current.

Tetrode Constants. The mu of a tetrode is usually very high, in some cases being as high as 600 or more. The plate resistance, too, is very much higher than that of most triodes, sometimes reaching a value of 1 megohm or more. On the other hand, the transconductance of a tetrode is more like that of a triode. As you know, G_m decreases as r_p increases, and with very high values of r_p we can expect low values of G_m. Then too, $G_m = \mu/r_p$. In a tetrode, the plate resistance grows faster than the mu, so the ratio of μ/r_p is usually small.

Figure 22-12 shows the plate family for a later type 24-A tube made with a plate that does not give up secondary electrons as easily as did the earlier type. Each curve

24-A

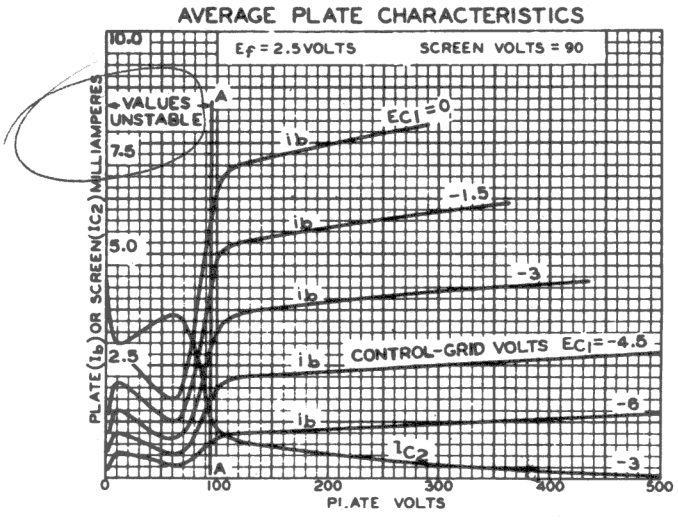


Fig. 22-12

shows the plate current for different values of plate voltage when the tube operates with a particular control-grid voltage and with 90 volts on the screen. Note that the plate current never drops below zero, as it did in the earlier type as shown in the last graph.

Few tetrode tubes are now being made for use in radio or television receivers.

22-3. PENTODES

You remember from your study of Lesson 19 that the pentode has a third grid that is normally tied to the cathode or to ground. This grid is called the suppressor grid, abbreviated, G_3. Its purpose, you recall, is to cancel the effects of secondary emission. Because the suppressor grid is at cathode or ground potential, it repels any secondary electrons that leave the plate and causes them to turn right around and return to the plate.

The plate family for a typical pentode is shown in Fig. 22-13. There is a curve for each value of grid voltage from zero to –5 volts in 1-volt steps. The screen voltage, e_{c2}, is shown to be fixed at 100 volts. The suppressor grid is tied to ground as is the cathode, so the potential difference between them, e_{c3}, is zero. Let's see what this family of curves can tell us.

Remembering the tetrode, the first thing we notice is that the plate current never

drops as the plate voltage increases – there are none of those dips where plate current reverses itself. We can see that the current rises rapidly at first but that it levels off much sooner than it does in the tetrode. As soon as the plate current gets into the level area beyond the knee of the curve, it becomes practically independent of the plate voltage. There is one very important thing to be seen as we look at this family of curves. The changes in plate current are not equal for equal changes in grid voltage. While we may not see this at a glance, a closer inspection will prove the statement to be true. Find the 200-volt line on the plate voltage axis. Note that the plate current is 0.63 ma with –5 volts on the grid. The difference between i_b at this point and i_b when the grid is at –4 volts is 1.00 ma; as the grid changes from –4 volts to –3 volts, the plate current changes 1.37 ma; as the grid changes from –3 volts to –2 volts, the plate current changes 1.8 ma, as the grid changes from –1 volts to zero, the plate current changes 2.2 ma. You can repeat this at the 150-volt, 250-volt, or any other plate voltage point with about the same results.

Even though equal changes in grid voltage do not produce equal changes in plate current, great amplification with minimum distortion can be obtained by means of the proper selection of operating characteristics.

A pentode like the 6SJ7 (for which these curves were drawn) has an amplification factor as high as 1,600, which is greater than any triode.

Beam-Power Tubes. Certain tetrodes and pentodes are made to handle greater amounts of electrical power than the tubes we have been speaking of are capable of handling. In these tubes, called *beam-power* tubes, electrons are formed into beams. Such a tube consists of a heater and cathode or a filament, a control grid, a screen grid, a plate, and, in some cases, a suppressor grid. The symbols for beam-power tubes are the same as for a pentode. Where no suppressor grid is used (as in Fig. 22-14), the electrodes are so arranged that the secondary emission is suppressed by space-charge effects between the plate and screen grid. Let's see how this is done.

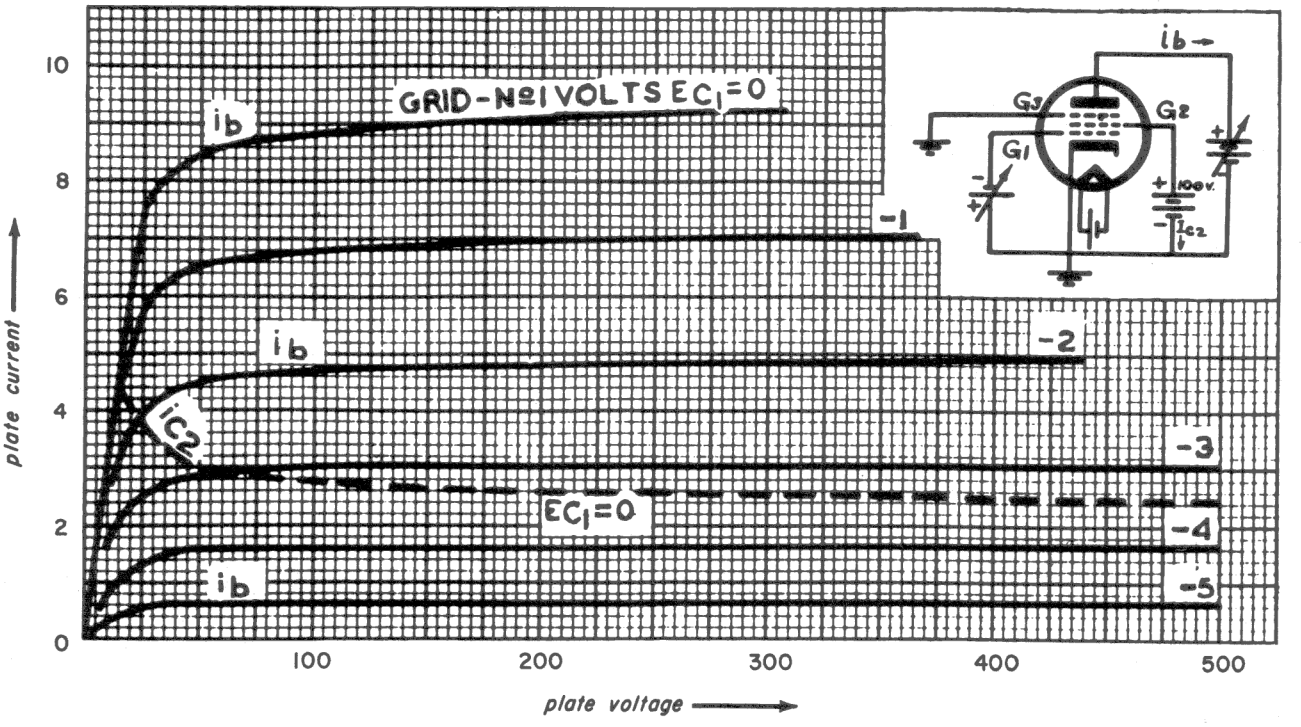


Fig. 22-13

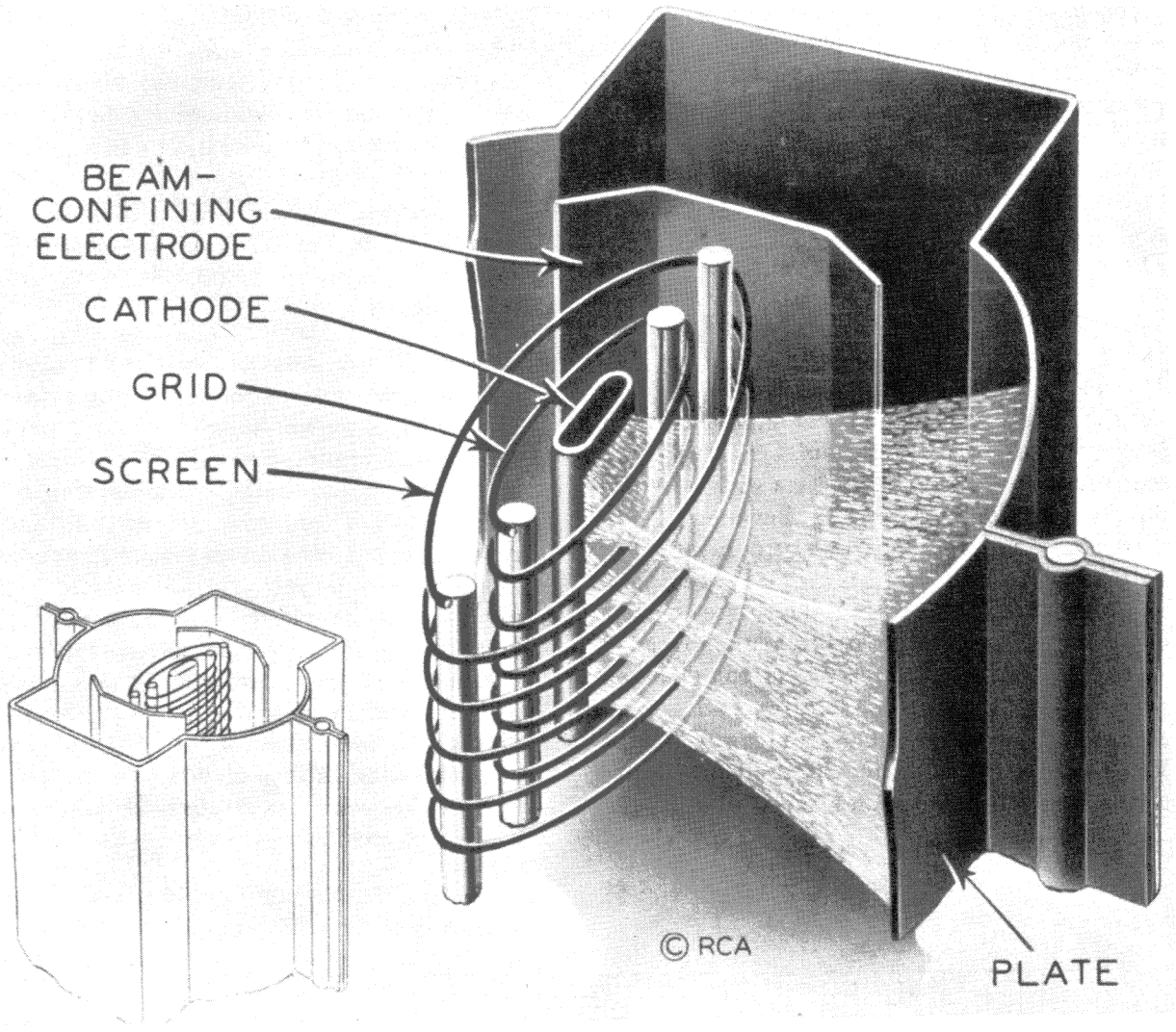
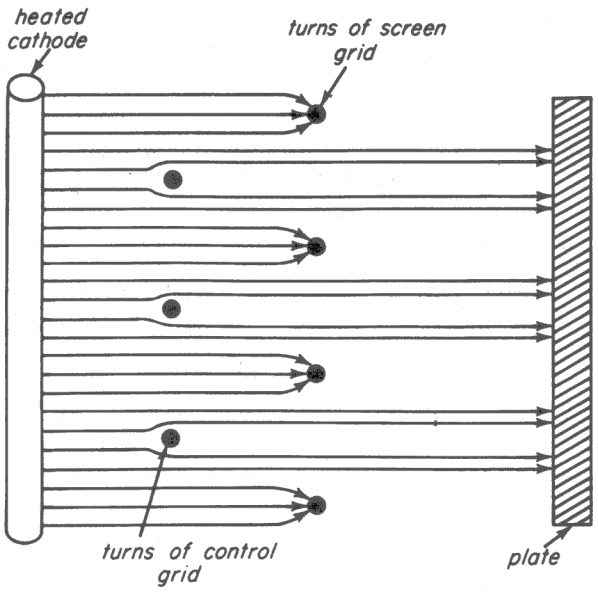


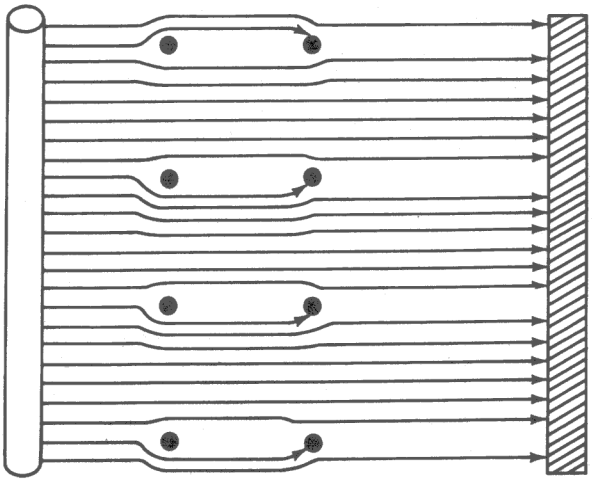
Fig. 22-14

Figure 22-15*a* shows the electron path in an ordinary tetrode. Some of the electrons that pass the control grid are directly attracted to the screen grid, because it is right in their path. These electrons form the screen current and limit the plate current. Where the control and screen grids are arranged (Fig. 22-15*b*) so that they spiral in a way that each turn of one is in line with each turn of the other, the screen grid is in the shadow of the control grid and many more electrons pass by the screen and go on to the plate. This produces a smaller screen current and a greater plate current. Such beam-power tubes are made with beam-forming plates (shown in the figure), which act to prevent stray electrons in the area between the plate and screen from getting to the screen. Figure 22-16*a* shows the relative position of the electrodes and beam-forming plates of such a tube, while Fig. 22-16*b* shows how the beam-forming plates limit the path of the electrons. The beam-forming plates are connected, inside the tube, to the cathode. Therefore, they are at cathode potential and form a negatively-charged field that is called a *virtual cathode*, which means it acts like and has the same effect as a cathode. Let's see how this can be.

We'll follow an electron as it travels from the cathode until it reaches the plate and see what forces act upon it. Figure 22-17*a* shows a side view and Fig. 22-17*b* shows a top view of the elements of a beam-power tube. In Fig. 22-17*a* an electron has just been emitted by the cathode and is in position *A*, between the cathode and control grid. It is attracted by the positive potential on the screen and the plate and is



(a)



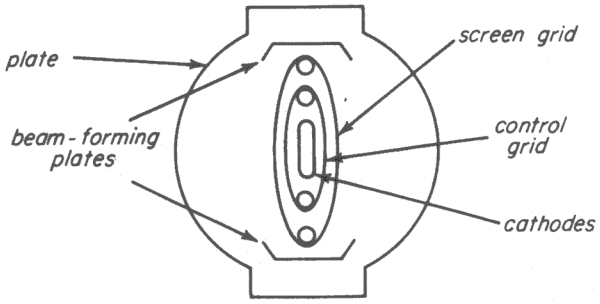
(b)

Fig. 22-15

repelled by the potential on the control grid. As a result, it avoids the control grid as it speeds up on its way toward the screen and plate.

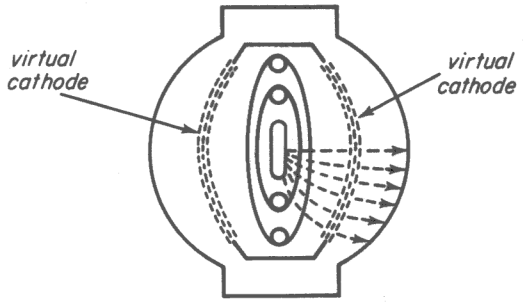
In avoiding contact with the control grid, the electron follows a path that is more or less straight toward the plate, and we find it in position *B*. Because the screen-grid turns are directly in line with the control-grid turns and the electron is going at high velocity, it tends to speed right by the screen grid even though it may be deflected slightly toward it by the screen's positive charge.

Of course, not all electrons are able to get by the screen; some are pulled to the



top view of beam-power elements

(a)



electron stream of beam-power tube

(b)

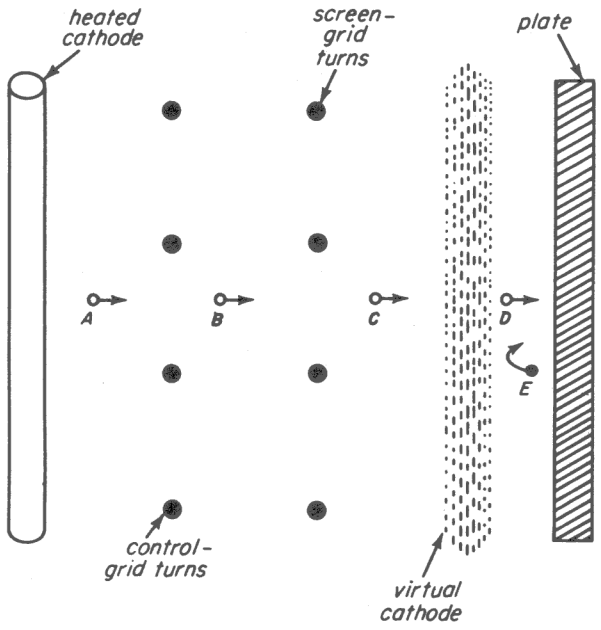
Fig. 22-16 /

screen and so form screen-grid current. However, we'll assume that the electron gets safely by the screen and is in position *C*. In passing the screen grid, the electron finds itself being slowed down by the zero-potential field of the beam-forming plates. Any electrons following our electron will be slowed down not only by the field of the beam-forming plates but also by the negative charge of our electron. As a result, a space charge is formed between the screen grid and plate. This space charge, formed by the field of the beam-forming plates and the presence of relatively slow moving electrons, is what is called the virtual cathode because it has zero potential and practically zero electron velocity.

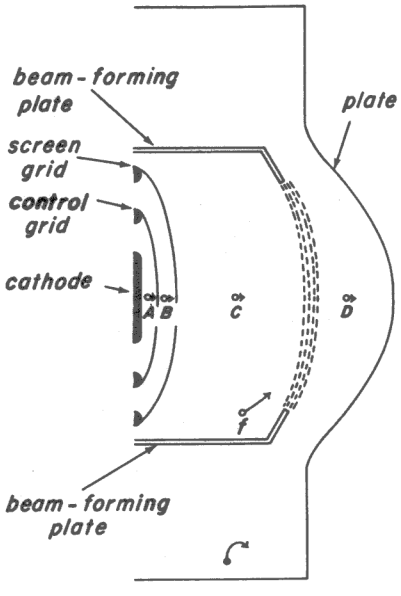
However, the positive charge on the plate pulls at our electron, and we next find it in position *D* on its way to the plate. The space charge between the screen and plate repels any electrons that may be knocked off the plate (such as that at *E*), so it acts like a suppressor grid to reduce secondary emission. The beam-forming plates also act to prevent stray electrons

from reaching the screen and forces them to go to the plate.

Because the beam-power tubes concentrate electrons into beams that are kept away from the screen as much as possible and forced in-



(a)



(b)

Fig. 22-17

to a direct path toward the plate, the screen current is very low and the plate current is very high, as may be seen by looking at Fig. 22-18, which shows the plate family for the 6L6 beam-power tube.

Note that the plate family for a beam-power tube has similar characteristics to

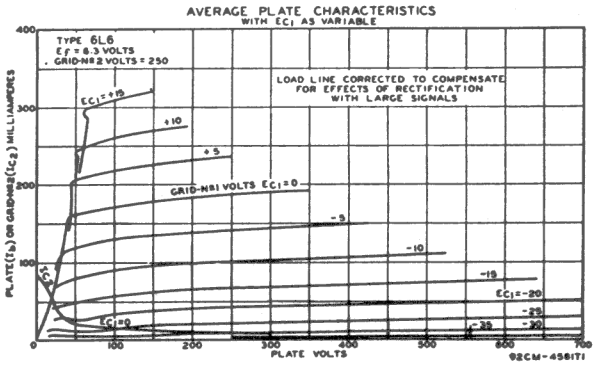
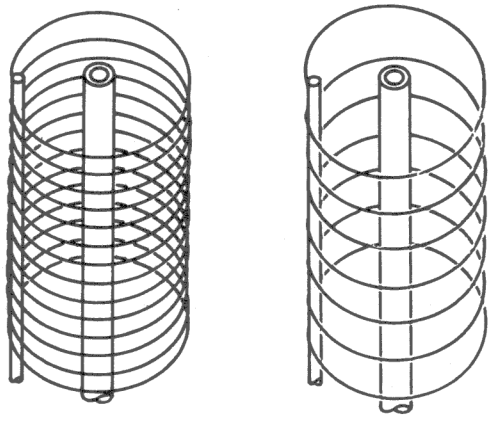


Fig. 22-18

that of a pentode tube. The plate resistance of the tube is lower, while the transconductance is higher than for a standard pentode. The beam-power tube has high power sensitivity and is found in many audio circuit applications.



(a) (b)

Fig. 22-19

22-4. VARIABLE-MU TUBES

Until now we have discussed and illustrated tubes that have control grids with evenly-spaced windings, as in Figs. 22-19*a* and *b*. We have said of such tubes that they have amplification factors that are practically constant. If we compare a closely-spaced grid (Fig. 22-19*a*) with an open-spaced grid (Fig. 22-19*b*), we find that a negative voltage applied to the closer grid winding has more effect on plate-current flow than the same voltage has when applied to the more open grid (when all other factors are held constant). For this reason, a tube with a closely-wound grid reaches plate-current cutoff sooner than does a tube with a more openly-wound grid. This is important because it is possible to make a tube having a variable mu. The tube with a closely-

wound grid has a higher mu, than one with an openly-wound grid.

By combining the openly-wound and closely-wound grid, it is possible to have a tube with a variable mu characteristic. Shown in Fig. 22-20 is such a grid.

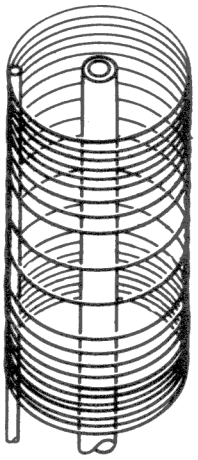


Fig. 22-20

The use of this type of grid imparts to the tube a variable-mu characteristic. Incidentally, the term remote cutoff or supercontrol tube is often used instead of variable mu. For example, shown in Fig. 22-21 are two grid curves. One is for the 6SK7 which is a remote cutoff (variable mu) tube; the other is for the 6SJ7, a sharp cut-off tube. Notice the difference in the slope of the two curves. The sharp cut off tube's curve goes to cut-off rather quickly. That is, as the control grid voltage becomes more negative, the plate current decreases uniformly.

However, in the variable-mu tube, the plate current does not decrease as rapidly as the grid approaches cut-off.

The principle upon which the variable-mu tube works is not difficult to understand. The control grid of such a tube looks something like what is shown in Fig. 22-20. The grid is closely wound at each end and is more openly wound in the center portion.

At low values of negative grid voltage, the grid operates normally. With larger values of negative grid voltage, the upper and lower ends of the grid, where the turns are closely spaced, cut off the flow of electrons toward the plate, but the wider spaced windings of the center portion still permit electrons to pass. When the negative grid voltage becomes great enough, even the center portion of the grid stops the flow of electrons toward the plate, and plate-current cutoff is reached.

The most important application for variable-mu tubes is in receiver circuits where uniform output is required.

Many radio and television receiver amplifier tubes must handle high-voltage signals from powerful local stations as well

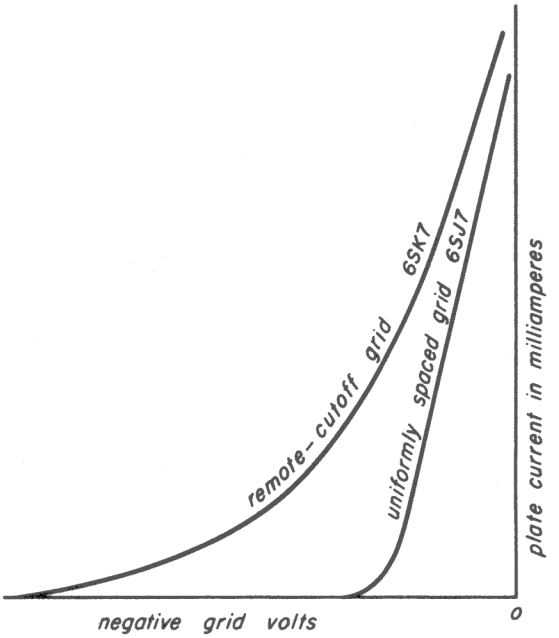


Fig. 22-21

as the lower-voltage signals from distant or low-powered transmitters, and produce the same magnitude of output.

Radio and television r-f and i-f amplifier tubes operate with a bias that varies with the strength of the signal. So, such tubes are usually variable-mu tubes capable of amplifying large variations in signal voltage with a minimum of distortion.

To understand how uniform output is obtained under varying signal conditions,

look at Fig. 22-22. For a weak signal the operating point will be at the upper part of the curve. Because of the slope of the curve at this point, maximum amplification takes place. However, when a strong signal is received, the lower operating point is chosen.

Notice that the two outputs have about the same magnitude. Thus, the variable mu tube is capable of developing uniform output for different signal levels. In actual practice, the choice of operating points is done electronically, by a circuit called the automatic-gain control or the automatic volume control. This will be discussed further when we study superheterodyne radio receivers.

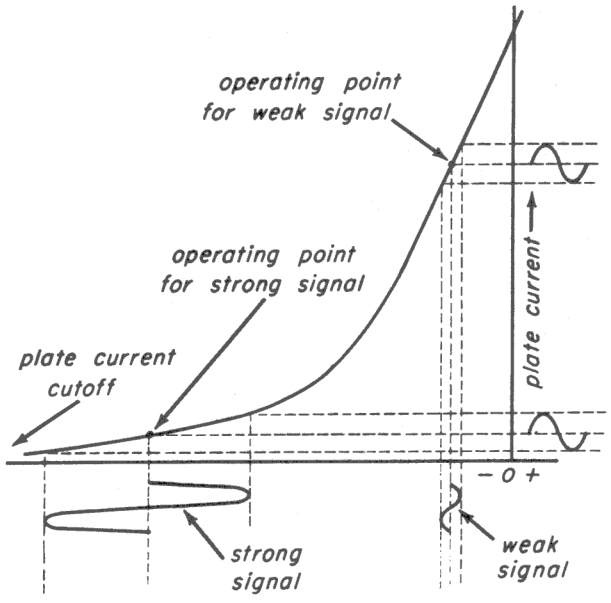


Fig. 22-22

APPENDIX A

We can find the derivation of the formula $\mu = r_p \times G_m$ as follows. We know that:

$$r_p = \frac{\Delta e_b}{\Delta i_b}$$

therefore:

$$\Delta e_b = r_p \times \Delta i_b \quad \text{and} \quad G_m = \frac{\Delta i_b}{\Delta e_c}$$

therefore:

$$\Delta e_c = \frac{\Delta i_b}{G_m} \quad \text{and} \quad \mu = \frac{\Delta e_b}{\Delta e_c}$$

by substitution:

$$\mu = \frac{r_p \times \Delta i_b}{\frac{\Delta i_b}{G_m}} = \Delta i_b \times r_p \times \frac{G_m}{\Delta i_b} = r_p \times G_m$$